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5th EDITION

Theory and Design for Mechanical Measurements

ternational Student Version

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International Student Version

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Preface

We are pleased to offer this 5^{th} *edition* of *Theory and Design for Mechanical Measurements*. This text provides a well-founded background in the theory of engineering measurements. Integrated throughout are the necessary elements for the design of measurement systems and measurement test plans, with an emphasis on the role of statistics and uncertainty analyses in design. The measurements field is very broad, but through careful selection of the topical coverage we establish the physical principles and practical techniques for many engineering applications while keeping page count and text cost manageable. Our aim is not to offer a manual for instrument construction and assembly. Instead, we develop the conceptual design framework for selecting and specifying equipment and test procedures and for interpreting test results, which we feel are necessary and common bases for the practice of test engineering. The text is appropriate for undergraduate and graduate level study in engineering, but is also suitably advanced and oriented to serve as a reference source for professional practitioners. The pedagogical approach invites independent study or use in related fields requiring an understanding of instrumentation and measurements.

The organization of the text develops from our view that certain aspects of measurements can be generalized, such as test plan design, signal analysis and reconstruction, and measurement system response. Topics such as statistics and uncertainty analysis require a basic development of principles but are then best illustrated by integrating these topics throughout the text material. Other aspects are better treated in the context of the measurement of a specific physical quantity, such as strain or temperature.

PEDAGOGICAL TOOLS TO AID LEARNING

In this textbook:

- Each chapter begins by defining a set of **learning outcomes**.
- The text develops an **intuitive understanding** of measurement concepts with its focus on test system modeling, test plan design, and uncertainty analysis.
- Each chapter includes carefully constructed **example problems** that illustrate new material and problems that build on prior material.
- Each example makes use of a **KNOWN, FIND, SOLVE** approach as an organizational aid to a problem's solution. This methodology for problem solutions helps new users to link words and concepts with symbols and equations. Many problems contain **COMMENTS** that expand on the solution, provide a proper context for application of the principle, or offer design application insight.
- **End-of-Chapter practice problems** are included for each chapter to exercise new concepts.
  - Practice problems range from those focused on concept development, to building of advanced skills, to open-ended design applications.
  - With each chapter, we have added new practice problems but have substantially "refreshed" many problems from previous editions.
  - We provide a detailed Instructors Manual for instructors who have adopted the book. We have carefully reviewed the solutions in this edition to minimize typographical and arithmetical errors. The manual is available on-line at the Wiley Instructor's website.
  - Answers to selected problems will be posted on the Wiley website.
- Use of the software in problem solving allows in-depth exploration of key concepts that would be prohibitively time consuming otherwise. The text includes on-line access to **interactive software** of focused examples based on software using National Instruments Labview® for exploring some of the

text concepts, while retaining our previous efforts using Matlab®. The Labview programs are available as executables so they can be run directly without a Labview license. The software is available on both the Wiley Student and Instructor's websites.

NEW TO THIS 5TH EDITION

With this 5th edition, we have new or expanded material on a number of topics. As highlights:

- We introduce Monte Carlo simulation methods in Chapter 4 and tie their use with uncertainty estimations in Chapter 5.
- Treatment of uncertainty analysis in Chapter 5 has been updated to include changes in test standards methodology relative to ASME PTC 19.1 Test Uncertainty and the International Standards Organization (ISO) Guide to Uncertainty in Measurements. These changes have been carried into the other chapters both in language and in example problems. Where we deviate from the methodology of the Standards, we do so for pedagogical reasons.
    - Discussion has been added on using rectangular (uniform) distributions in uncertainty estimation.
    - The treatment of non-symmetric uncertainty intervals and methods for treating correlated errors in Chapter 5 has been expanded and revisited in other chapters.
    - We have updated our symbol usage for closer consistency with the standards.
- We have added a section presenting image acquisition and processing using digital techniques in Chapter 7.
- We have changed our presentation of pressure transmission line effects to make better use of the lumped parameter methods of Chapter 3 that engineering students are familiar with, including discussion of the ideal elements of inertance, resistance, and compliance.
- We have revised our treatment of Butterworth filters, including added coverage, in Chapter 6.
- We have added an introduction to the analysis of strain gauge data to compute principal stresses in Chapter 11.

SUGGESTED COURSE COVERAGE

To aid in course preparation, Chapters 1 through 5 provide an introduction to measurement theory with statistics and uncertainty analysis, Chapters 6 and 7 provide a broad treatment of analog and digital sampling methods, and Chapters 8 through 12 are instrumentation focused.

Many users report to us that they use different course structures, so many that it makes a preferred order of topical presentation difficult to anticipate. To accommodate this, we have written the text in a manner that allows any instructor to customize the order of material presentation. While the material of Chapters 4 and 5 are integrated throughout the text and should be taught in sequence, the other chapters tend to stand on their own. The text is flexible and can be used in a variety of course structures at both the undergraduate and graduate levels.

For a complete measurements course, we recommend the study of Chapters 1 through 7 with use of the remaining chapters as appropriate. For a lab-course sequence, we recommend using chapters as they best illustrate the course exercises while building complete coverage over the several lab courses normally within a curriculum. The manner of the text allows it to be a resource for a lab-only course with minimal lecture. Over the years, we have used it in several forums, as well as professional development courses, and simply rearrange material and emphasis to suit the audience and objective.

We express our sincerest appreciation to the students, teachers, and engineers who have used our earlier editions. We are indebted to the many who have written us with their constructive comments and encouragement.

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Contents

Chapter 1

Basic Concepts of Measurement Methods

1.1 INTRODUCTION

We make measurements every day. Consider the common measurements illustrated in Figure 1.1. We routinely read the temperature of an outdoor thermometer to choose appropriate clothing for the day. We expect to have exactly 10 gallons or liters of fuel added to our tank when that volume is indicated on a fuel pump. And we expect measuring cups to yield correct quantities of ingredients in cooking. We put little thought into the selection of instruments for these routine measurements. After all, the direct use of the data is clear to us, the type of instruments and techniques are familiar to us, and the outcome of these measurements is not important enough to merit much attention to features like improved accuracy or alternative methods. But when the stakes become greater, the selection of measurement equipment and techniques and the interpretation of the measured data can demand considerable attention. Just contemplate how you might verify that a new engine is built as designed and meets the power and emissions performance specifications required.

But first things first. The objective in any measurement is to answer a question. So we take measurements to establish the value or the tendency of some variable, the results of which are specifically targeted to answer our question. The information acquired is based on the output of the measurement device or system. There are important issues to be addressed to ensure that the output of the measurement device is a reliable indication of the true value of the measured variable. In addition, we must address the following important questions:

1. How can a measurement or test plan be devised so that the measurement provides the unambiguous information we seek?
2. How can a measurement system be used so that the engineer can easily interpret the measured data and be confident in their meaning?

There are procedures that address these measurement questions.

At the onset, we want to stress that the subject of this text is real-life oriented. Specifying a measurement system and measurement procedures represents an open-ended design problem whose outcome will not have one particular solution. That means there may be several approaches to solving a measurement problem, and some will be better than others. This text emphasizes accepted procedures for analyzing a measurement problem to assist in the selection of equipment,

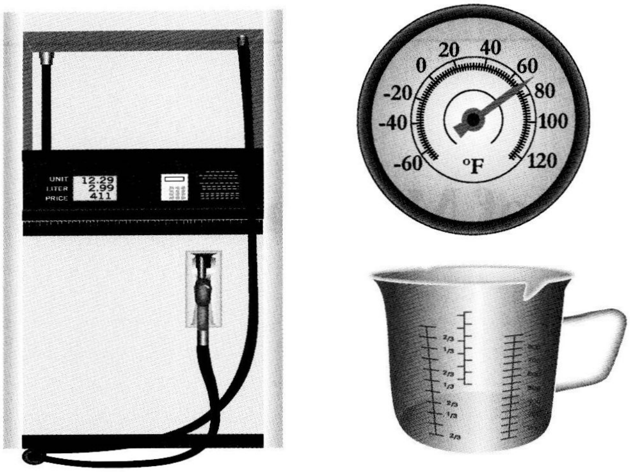

Figure 1.1 Common devices that involve measurements.

methodology, and data analysis to meet the design objectives. Perhaps more than in any other technical field, the approach taken in measurement design and the outcome achieved will often depend on the attention and experience of the designer.

Upon completion of this chapter, the reader will be able to

- identify the major components of a general measurement system, and state the function of each,
- develop an experimental test plan,
- distinguish between random and systematic errors,
- describe and define the various error types,
- define a standard and distinguish among primary, secondary, and transfer standards, and
- clearly delineate defined and derived dimensions in various unit systems.

1.2 GENERAL MEASUREMENT SYSTEM

A *measurement*[1] is an act of assigning a specific value to a physical variable. That physical variable is the *measured variable*. A measurement system is a tool used for quantifying the measured variable. As such, a measurement system is used to extend the abilities of the human senses that, while they can detect and recognize different degrees of roughness, length, sound, color, and smell, are limited and relative; they are not very adept at assigning specific values to sensed variables.

A system is composed of components that work together to accomplish a specific objective. We begin by describing the components that make up a measurement system, using specific examples. Then we will generalize to a model of the generic measurement system.

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[1] There are many new engineering measurement terms introduced. A glossary of the italicized terms is located in the back of the text for your reference.

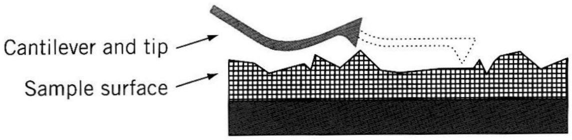

Figure 1.2 Sensor stage of an atomic-force microscope.

Sensor and Transducer

An increasingly important area of scientific inquiry is the characteristics of matter at the nanoscale. Suppose we want to measure the profile of a surface at a nanometer scale. We discover that a small (very small) cantilever beam placed near the surface is deflected by atomic forces. Let's assume for now that they are repulsive forces. If this cantilever is translated over the surface, the cantilever will deflect, indicating the height of the surface. This concept is illustrated in Figure 1.2; the device is called an atomic force microscope. The cantilever beam is a *sensor*, a physical element that employs some natural phenomenon, in this case deflection under the action of a force, to sense the variable being measured, in this case the height of the surface.

So, we have a sensor to measure at the nanometer scale. But we have no means of getting an output from the sensor that we can record. Suppose that the upper surface of the cantilever is reflective, and we shine a laser onto the upper surface, as shown in Figure 1.3. The movement of the cantilever will deflect the laser. Employing a number of light sensors, also shown in Figure 1.3, the deflection of the laser can be sensed and that deflection corresponds to the height of the surface. Together the laser and the light sensors (photodiodes) form the transducer component of the measurement system. A transducer converts the sensed information into a detectable signal. The signal might be mechanical, electrical, optical, or may take any other form that can be meaningfully recorded.

We should note that sensor selection, placement, and installation are particularly important to ensure that the sensor output accurately reflects the measurement objective. The familiar phrase

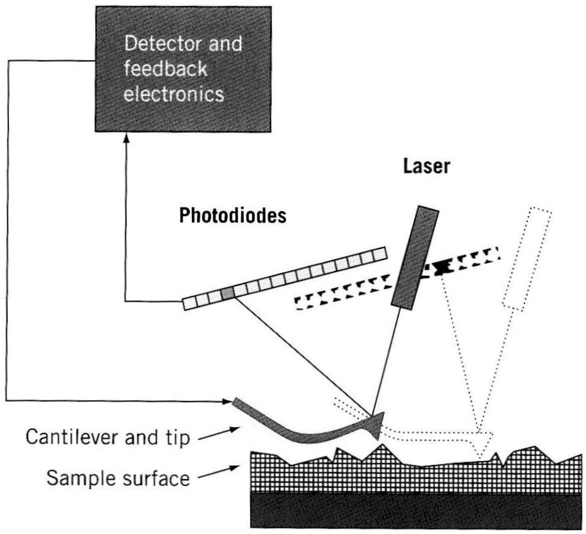

Figure 1.3 Atomic-force microscope with sensor and transducer stages.

associated with hot days, "100°F in the shade" implies a specific sensor placement. Accordingly, the interpretation of all information passed through and indicated by the system depends on what is actually sensed by the sensor. For example, the interpretation of the output of a medical thermometer depends on where its sensor is placed.

Output Stage

The goal of a measurement system is to convert the sensed information into a form that can be easily quantified. Consider a familiar example, the liquid-in-glass bulb thermometer. The liquid contained within the bulb on the common bulb thermometer of Figure 1.4 exchanges energy with its surroundings until the two are in thermal equilibrium. At that point they are at the same temperature. This energy exchange is the input signal to this measurement system. The phenomenon of thermal expansion of the liquid results in its movement up and down the stem, forming an output signal from which we determine temperature. The liquid in the bulb acts as the sensor. By forcing the expanding liquid into a narrow capillary, this measurement system transforms thermal information into a mechanical displacement. Hence, the bulb's internal capillary design acts as a transducer.

The *output stage* indicates or records the value measured. This might be a simple readout display, a marked scale, or even a recording device such as a computer disk drive. The readout scale of the bulb thermometer in Figure 1.4 serves as the output stage of that measurement system.

It is worth noting that the term "transducer" is also often used in reference to a packaged device, which may contain a sensor, transducer, and even some signal conditioning elements. While such terminology is not true to our presentation, the context in which the term is used prevents ambiguity.

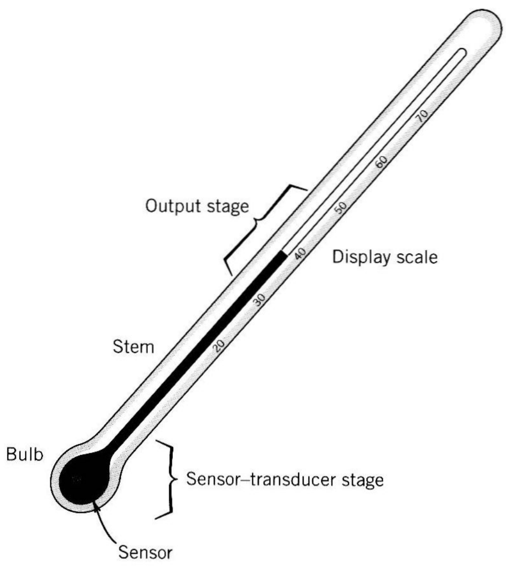

Figure 1.4 Components of bulb thermometer equivalent to sensor, transducer, and output stages.

General Template for a Measurement System

A general template for a measurement system is illustrated in Figure 1.5. Basically such a system consists of part or all of four general stages: (1) sensor–transducer stage, (2) signal-conditioning stage, (3) output stage, and (4) feedback-control stage. These stages form the bridge between the input to the measurement system and the system output, a quantity that is used to infer the value of the physical variable measured. We discuss later how the relationship between the input information, as acquired by the sensor, and the system output is established by a calibration. We have already discussed the sensor–transducer stage, so let's move on to the signal-conditioning stage.

The *signal-conditioning stage* takes the transducer signal and modifies it to a desired magnitude. This optional intermediate stage might be used to perform tasks such as increasing the magnitude of the signal by amplification, removing portions of the signal through some filtering technique, or providing mechanical or optical linkage between the transducer and the output stage. For example, the translational displacement of a mechanic's caliper (sensor) is often converted into a rotational displacement of a pointer. This stage can consist of one or more devices, which are often connected in series. For example, the diameter of the thermometer capillary relative to the bulb volume (see Fig. 1.4) determines how far up the stem the liquid moves with increasing temperature. It "conditions" the signal by amplifying the liquid displacement.

In those measurement systems involved in process control, a fourth stage, the *feedback-control stage,* contains a controller that interprets the measured signal and makes a decision regarding the control of the process. This decision results in a signal that changes the process parameter that affects the magnitude of the sensed variable. In simple controllers, this decision is based on the magnitude of the signal of the sensed variable, usually whether it exceeds some high or low set point, a value set by the system operator. For example, a simple measurement system with control stage is a household furnace thermostat. The operator fixes the set point for temperature on the thermostat display, and the furnace is activated as the local temperature at the thermostat, as determined by the

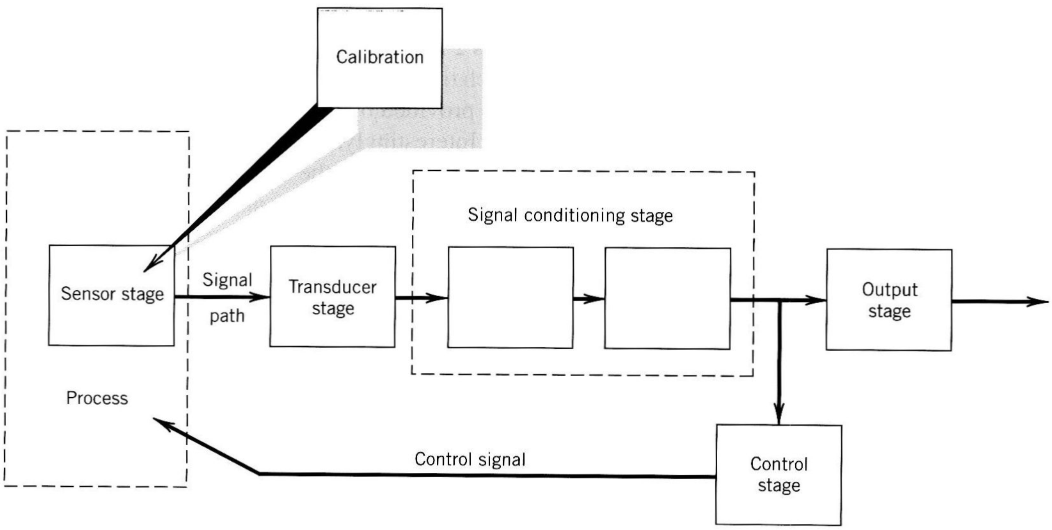

Figure 1.5 Components of a general measurement system.

sensor within the device, rises or falls above or below the set point. In a more sophisticated controller, a signal from a measurement system can be used as an input to an "expert system" controller that, through an artificial intelligence algorithm, determines the optimum set conditions for the process. *Mechatronics* deals with the interfacing of mechanical and electrical components with microprocessors, controllers, and measurements. We will discuss some features of mechatronic systems in detail in Chapter 12.

1.3 EXPERIMENTAL TEST PLAN

An experimental test serves to answer a question, so the test should be designed and executed to answer that question and that question alone. This is not so easy to do. Let's consider an example.

Suppose you want to design a test to answer the question, "What is the fuel use of my new car?" What might be your test plan? In a test plan, you identify the variables that you will measure, but you also need to look closely at other variables that will influence the result. Two important variables to measure would be distance and fuel volume consumption. Obviously, the accuracy of the odometer will affect the distance measurement, and the way you fill your tank will affect your estimate of the fuel volume. But what other variables might influence your results? If your intended question is to estimate the average fuel usage to expect over the course of ownership, then the driving route you choose would play a big role in the results and is a variable. Only highway driving will impose a different trend on the results than only city driving, so if you do both you might want to randomize your route by using various types of driving conditions. If more than one driver uses the car, then the driver becomes a variable because each individual drives somewhat differently. Certainly weather and road conditions influence the results, and you might want to consider this in your plan. So we see that the utility of the measured data is very much impacted by variables beyond the primary ones measured. In developing your test, the question you propose to answer will be a factor in developing your test plan, and you should be careful in defining that question so as to meet your objective.

Imagine how your test conduct would need to be different if you were interested instead in providing values used to advertise the expected average fuel use of a model of car. Also, you need to consider just how good an answer you need. Is 2 liters per 100 kilometers or 1 mile per gallon close enough? If not, then the test might require much tighter controls. Lastly, as a concomitant check, you might compare your answer with information provided by the manufacturer or independent agency to make sure your answer seems reasonable. Interestingly, this one example contains all the same elements of any sophisticated test. If you can conceptualize the factors influencing this test and how you will plan around them, then you are on track to handle almost any test. Before we move into the details of measurements, we focus here on some important concepts germane to all measurements and tests.

Experimental design involves itself with developing a measurement test plan. A test plan draws from the following three steps:[2]

1. ***Parameter design plan.*** Determine the test objective and identify the process variables and parameters and a means for their control. Ask: "What question am I trying to answer? What needs to be measured?" "What variables and parameters will affect my results?"

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[2] These three strategies are similar to the bases for certain design methods used in engineering system design (1).

2. ***System and tolerance design plan.*** Select a measurement technique, equipment, and test procedure based on some preconceived tolerance limits for error.[3] Ask: "In what ways can I do the measurement and how good do the results need to be to answer my question?"
3. ***Data reduction design plan.*** Plan how to analyze, present, and use the anticipated data. Ask: "How will I interpret the resulting data? How will I use the data to answer my question? How good is my answer? Does my answer make sense?"

Going through all three steps in the test plan before any measurements are taken is a useful habit for a successful engineer. Often, step 3 will force you to reconsider steps 1 and 2! In this section, we focus on the concepts related to step 1 but will discuss and stress all three throughout the text.

Variables

Once we define the question that we want the test to answer, the next step is to identify the relevant process parameters and variables. Variables are entities that influence the test. In addition to the targeted measured variable, there may be other variables pertinent to the measured process that will affect the outcome. All known process variables should be evaluated for any possible cause-and-effect relationships. If a change in one variable will not affect the value of some other variable, the two are considered independent of each other. A variable that can be changed independently of other variables is known as an *independent variable.* A variable that is affected by changes in one or more other variables is known as a *dependent variable.* Normally, the variable that we measure depends on the value of the variables that control the process. A variable may be continuous, in that its value is able to change in a continuous manner, such as stress under a changing load or temperature in a room, or it may be discrete in that it takes on discrete values or can be quantified in a discrete way, such as the value of the role of dice or a test run by a single operator.

The *control* of variables is important. A variable is controlled if it can be held at a constant value or at some prescribed condition during a measurement. Complete control of a variable would imply that it can be held to an exact prescribed value. Such complete control of a variable is not usually possible. We use the adjective "controlled" to refer to a variable that can be held as prescribed, at least in a nominal sense. The cause-and-effect relationship between the independent variables and the dependent variable is found by controlling the values of the independent variables while measuring the dependent variable.

Variables that are not or cannot be controlled during measurement but that affect the value of the variable measured are called *extraneous variables*. Their influence can confuse the clear relation between cause and effect in a measurement. Would not the driving style affect the fuel consumption of a car? Then unless controlled, this influence will affect the result. Extraneous variables can introduce differences in repeated measurements of the same measured variable taken under seemingly identical operating conditions. They can also impose a false trend onto the behavior of that variable. The effects due to extraneous variables can take the form of signals superimposed onto the measured signal with such forms as noise and drift.

[3] The tolerance design plan strategy used in this text draws on uncertainty analysis, a form of sensitivity analysis. Sensitivity methods are common in design optimization.